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Effects of Lorentz invariance violation on particle acceleration and photon emission

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In this study, we revisit the models of Fermi acceleration, incorporating Lorentz Invariance Violation (LIV) through a phenomenological approach. LIV is introduced via a modified Einstein's dispersion relation, along with an adjustment to the Lorentz factor. We calculate the energy spectrum and acceleration time of particles accelerated by first- and second-order Fermi mechanisms as a function of the energy at which LIV becomes significant. The second-order mechanism exhibited a shift in the spectral index, while the first-order model exhibited a significant suppression in the particle spectrum. Additionally, Synchrotron and Synchrotron Self-Compton (SSC) losses were incorporated into the first-order energy spectrum, with these processes also being modified by LIV. The effects on the spectra of charged particles were analyzed, as well as the resulting photon emissions from these losses. Synchrotron losses induced an energy barrier, while SSC led to a suppression in the number of particles. The LIV-modified SSC emission resulted in a new high-energy emission region, which is not observed in standard scenarios. This work advances the search for LIV in astroparticle physics by demonstrating, for the first time, how this hypothesis alters Fermi acceleration mechanisms, paving the way for a more comprehensive analysis in the future.

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1. Introduction

Einstein's theory of relativity has been a cornerstone of modern physics since its inception, providing the foundation for our current understanding of space and time. However, high-energy theoretical frameworks — particularly those aiming at quantum gravity and unification — predict the possibility of deviations from Lorentz invariance, which is known as Lorentz Invariance Violation (LIV) [1].

To date, searches for LIV have primarily placed constraints through particle propagation [2]. Nevertheless, this focus overlooks a crucial aspect: the dynamics of charged particle acceleration and the radiative processes they undergo in extreme astrophysical environments, where effects induced by LIV could manifest in distinctive ways.

In this work, we present the analysis of LIV-induced corrections to Fermi acceleration mechanisms — both first- and second-order [3] — and investigate the direct consequences of LIV for photon emission through synchrotron and inverse Compton energy loss processes. Our approach paves the way for a more complete, multi-messenger methodology to constrain LIV parameters using astrophysical observations.

2. Lorentz invariance violation

Various theoretical frameworks incorporating Lorentz invariance violation predict deviations from the conventional Einstein's dispersion relation [4]. From a perturbative standpoint, this modification can be expressed as:

$$E^2 = m^2 + p^2 + \sum_n \delta_n p^{n+2}\,, \tag{1}$$

where we are considering natural units. The parameter n is the order of violation, while δ_n is a scaling factor that quantifies the intensity of LIV, which must be small, with its effects becoming significant only at high energies. In the high-energy regime ($p \gg m$), Equation 1 yields

$$p = \frac{E}{\sqrt{1+\delta_n E^n}}\,. \tag{2}$$

The Lorentz factor is also modified by LIV, whereby, derived from the group velocity, $v = \frac{\partial E}{\partial p}$, the correction takes the form:

$$\gamma_{\text{LIV}}^2 = \frac{E^2}{m^2 - (n+1)\delta_n E^{n+2}}\,. \tag{3}$$

When E exceeds $\frac{m^2}{(n+1)\,\delta_n}$, the modified Lorentz factor becomes mathematically negative, revealing a limitation in the perturbative approach of Equation 1. Thus, a new and complete model is required for the description at higher energies.

For LIV in photons, the parameter was denoted as $\delta_n^{(\gamma)}$, whereas for charged particles, δ_n was used.

3. Fermi acceleration models with LIV

In 1949, Enrico Fermi developed a theoretical framework for charged particle acceleration to account for the observed cosmic ray spectrum [5]. His original model, now referred to as second-order Fermi acceleration, proposed that particles gain energy through stochastic collisions with interstellar gas clouds. However, subsequent refinements led to the more efficient shock-wave acceleration mechanism, where particles are energized primarily through interactions with astrophysical shock discontinuities [6].

Below, we re-examine these acceleration models while incorporating LIV effects [3].

3.1 Second-order Fermi acceleration including LIV

Stochastic collisions between charged particles and gas clouds induce energy gain. This acceleration can be derived through Lorentz transformations, transitioning between the laboratory frame and the frame of a gas cloud with velocity V. When incorporating LIV effects, the calculated average energy gain for a particle with energy E yields a modified increment given by:

$$\left\langle \frac{\Delta E}{E} \right\rangle = \left[2 + \frac{2}{3\sqrt{1+\delta_n E^n}} \right] V^2. \tag{4}$$

If we set $\delta_n = 0$, Fermi's original result is re-obtained.

Following [7], it was possible to obtain the fundamental relation that defines the energy spectrum of particles [3]. The solution for the number of particles can be seen in Figure 1.

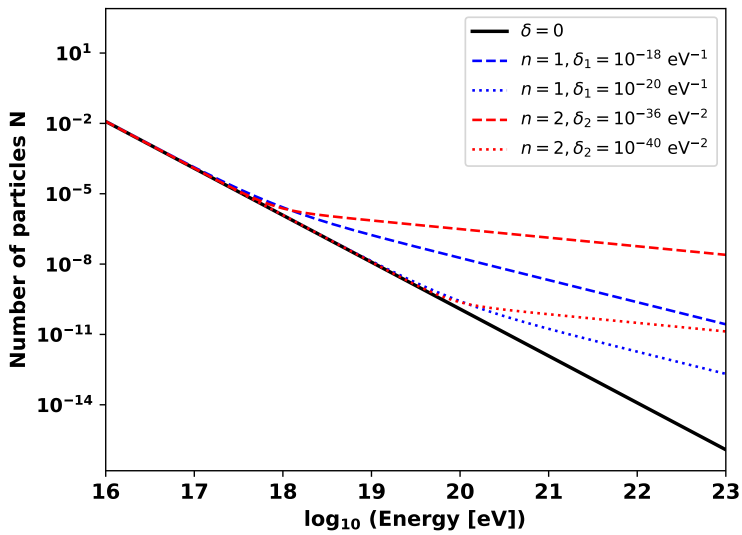

Figure 1: Energy spectrum of charged particles accelerated via the second-order Fermi mechanism when LIV is considered. Different LIV parameters are shown for the first two violation order, $n = 1$ and $n = 2$. This plot was reproduced from [3].

The introduction of LIV modifies the energy spectrum of charged particles, resulting in a spectral index that depends on the violation order n. Each order n yields a distinct spectral index, with the transition energy scale determined by the parameter δ_n.

3.2 First-order Fermi acceleration including LIV

First-order Fermi acceleration is defined by particle acceleration at a supersonic shock fronts, where particle fluxes exist on both the upstream and downstream sides. The shock propagates with velocity U in the laboratory reference frame, and the downstream and upstream regions have a relative velocity of $V = \frac{3}{4}U$. Under these conditions, incorporating LIV, a particle with energy E receives an average modified increment for a round trip given by

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3\sqrt{1+\delta_n E^n}} V. \tag{5}$$

If $\delta_n = 0$, we recover standard result.

The energy spectrum of charged particles was derived using Bell's formalism [8], where the diffusion-loss equation yields the spectral distribution. The results are displayed in Figure 2. As evident from the results, LIV introduction causes significant suppression of the particle energy spectrum. This is a direct consequence of the reduced energy gain at higher energies, quantified in Equation 5.

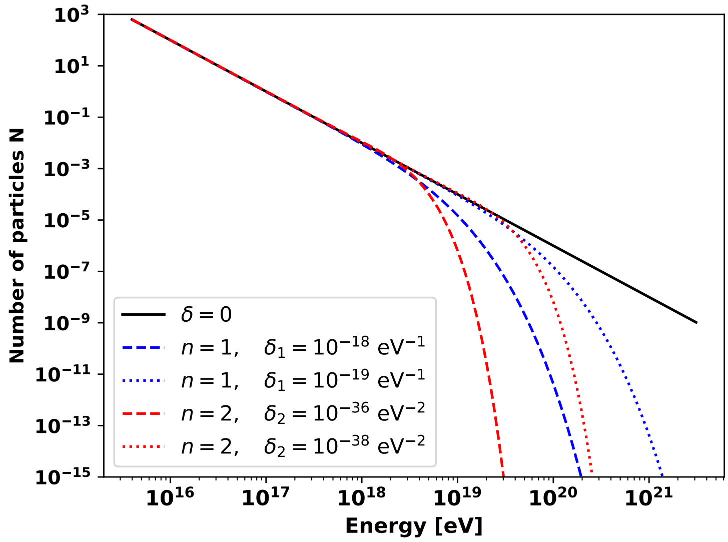

Figure 2: Energy spectrum of charged particles accelerated via the first-order Fermi mechanism when LIV is considered. Different LIV parameters are shown for the first two orders of violation, $n = 1$ and $n = 2$. This plot was reproduced from [3].

4. First-order Fermi mechanism with energy losses including LIV

To model the particle spectrum more realistically, energy loss mechanisms must be taken into account. Here, we revisited synchrotron and inverse Compton radiation processes, incorporating LIV effects within a first-order Fermi acceleration framework.

Furthermore, these energy loss processes are inherently linked to secondary photon emission [9]. The resulting energy spectrum of photons carries critical observational signatures, which

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can be used to probe source characteristics and test potential deviations from standard Lorentz-invariant physics.

4.1 Energy losses including LIV

Within magnetic fields, charged particles emit synchrotron radiation [10], with most photons being radiated near the critical energy. This characteristic energy is subject to modifications from LIV, with its altered expression given by:

$$E_\gamma^{\rm LIV} = 0.29 \cdot \frac{3}{2} \cdot \frac{qB}{m^3} \left[\frac{E^2}{1 - (n+1)\,\frac{\delta_n}{m^2} E^{n+2}} \right], \tag{6}$$

where q, m and E are the charge, mass and energy of the charged particle and B is the magnetic field. These modifications also affect the emitted power, which is now given by:

$$P^{\rm LIV} = \frac{2}{3}\frac{q^4}{m^4} |\vec{v} \times \vec{B}|^2 \left[\frac{E^2}{1 - (n+1)\,\frac{\delta_n}{m^2} E^{n+2}} \right] \tag{7}$$

with $\vec{v}$ being the particle's velocity. Both modifications exhibit identical behavior - a divergence as $E^{n+2} \rightarrow \frac{m^2}{(n+1)\,\delta_n}$, causing the power output to diverge. This creates an energy cutoff while simultaneously enabling photon emission at unexpectedly high energies.

We also examined the final energies in the inverse Compton process [11], where photons gain energy through interactions with high-energy charged particles. The post-interaction energies can be derived from 4-momentum conservation, yielding two key equations for LIV in photons:

$$E_p'^2 = m^2 + \left(\frac{E_\gamma'^2}{1 + \delta_n^{(\gamma)} E_\gamma'^n} + \frac{E_\gamma^2}{1 + \delta_n^{(\gamma)} E_\gamma^n} - \frac{2 E_\gamma E_\gamma' \cos\theta}{\sqrt{\left(1 + \delta_n^{(\gamma)} E_\gamma'^n\right)\left(1 + \delta_n^{(\gamma)} E_\gamma^n\right)}} \right) \tag{8}$$

and

$$m^2 + 2 m E_\gamma + E_\gamma^2 - E_\gamma'^2 - E_p'^2 - 2 E_\gamma' E_p' = 0\,. \tag{9}$$

The solution to this system is shown in Figure 3, calculated for the electron case. As can be seen, when LIV effects become significant, the Thomson scattering regime is restored. This effect is similarly manifested in both the cross-section and the mean scattering angle.

4.2 Energy spectrum of particles including LIV

Energy losses significantly impact the spectral shape of charged particles. Using a one-zone model, we can evaluate how each modified loss mechanism affects the particle spectrum [12]. We examined two dominant cases: synchrotron-dominated losses, and synchrotron self-Compton (SSC) dominated losses, where the photon background is created by the particles' own synchrotron radiation [13]. Figure 4 shows both cases when electrons are considered.

In the synchrotron-dominated case (Figure 4a), we observe a pronounced energy cutoff resulting from the power divergence, which prevents the acceleration of higher-energy particles. In contrast, for the SSC scenario (Figure 4b), the particle spectrum shows gradual suppression as the radiated power increases with LIV effects.

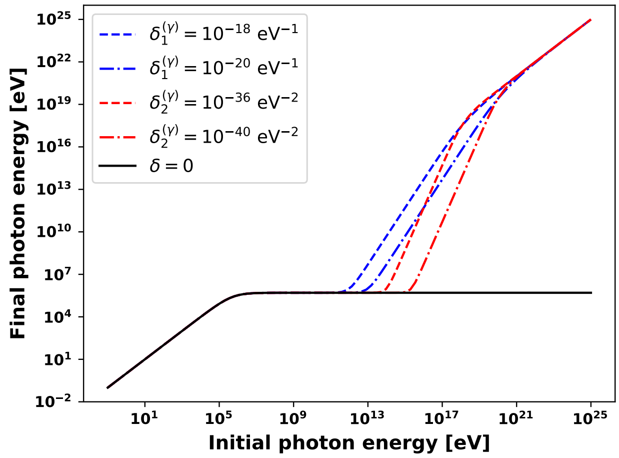
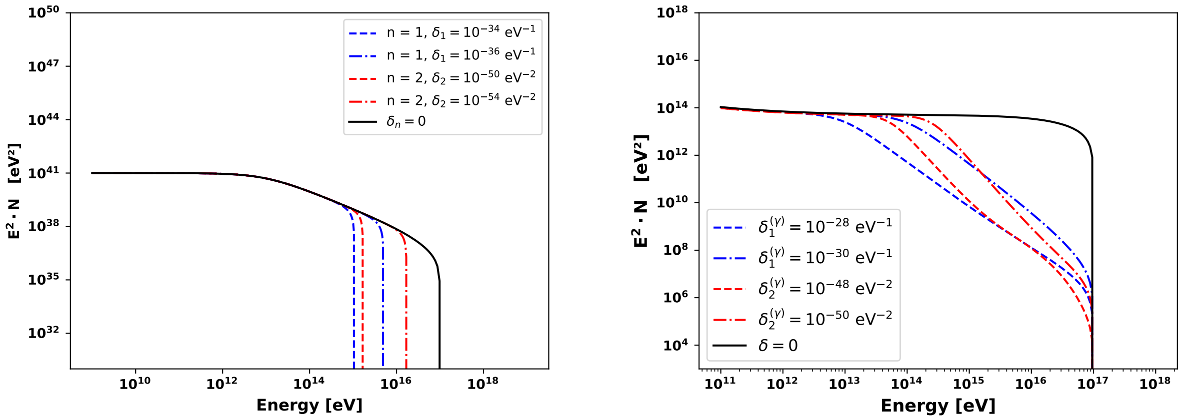


Figure 3: Energy of the photon after the interaction as a function of its initial energy. A scattering angle of $\pi/2$ was adopted. Different values of $\delta_n^{(\gamma)}$ are shown for the first two orders of violation. The electron LIV parameter was set to 0.



(a) Energy spectrum of charged particles when synchrotron is the dominant loss process.

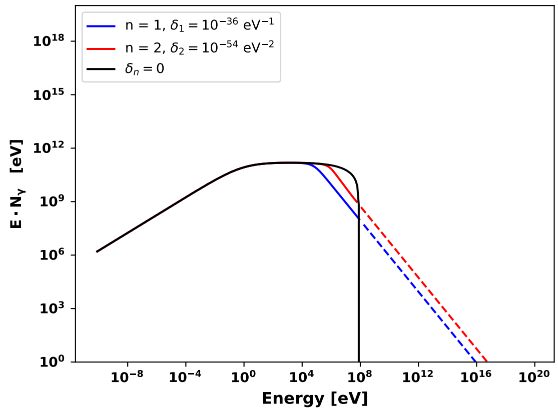
(b) Energy spectrum of charged particles when SSC is the dominant loss process.

Figure 4: Energy spectrum of charged particles accelerated via first-order Fermi mechanism and susceptible to losses including LIV. The energy of spectral index break was taken to be 10^{13} eV and $B = 10^{-10}$ T. Different values of $\delta_n^{(\gamma)}$ and δ_n are shown for the first two orders of violation.

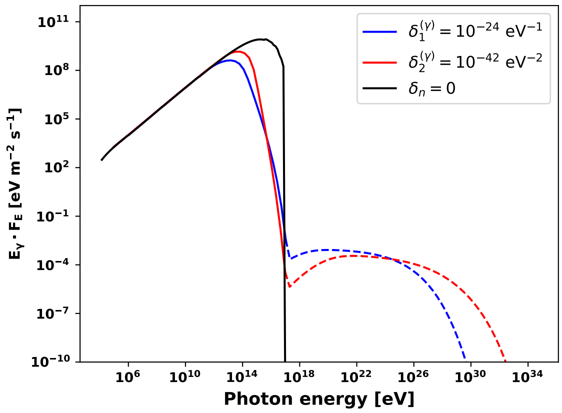
4.3 Energy spectrum of photons including LIV

For photon emission, we analyze each case separately: synchrotron emission when synchrotron losses dominate, and SSC emission when SSC losses dominate. The resulting spectral features are shown in Figure 5.

Both processes exhibit significant modifications when LIV effects are included. A new emission component emerges at ultra-high energies, while the low-energy portion of the spectrum is also altered due to electron spectral suppression.



(a) Energy spectrum of photons emitted via sync. when sync. is the dominant loss process.



(b) Energy spectrum of photons emitted via SSC when SSC is the dominant loss process.

Figure 5: Energy spectrum of photons emitted by each loss when LIV is included and the loss is taken as the dominant process. The energy of spectral index break was taken to be 10^{13} eV and $B = 10^{-10}$ T. Different values of $\delta_n^{(\gamma)}$ and δ_n are shown for the first two orders of violation. The dashed region indicates where energy conservation is violated.

5. Conclusion

Here, we present how Lorentz Invariance Violation (LIV) affects Fermi acceleration processes, as well as modifications to synchrotron and inverse Compton energy loss mechanisms, with a particular focus on their implementation in the first-order Fermi acceleration scenario.

LIV induces significant changes in both first- and second-order Fermi mechanisms. In the second-order case, we find a modification in the spectral index, whereas in the first-order mechanism, LIV leads to a strong suppression of particle acceleration when its effects become relevant.

Energy loss processes are also substantially altered. For synchrotron radiation, LIV introduces a divergence in both the emitted power and photon energy. When incorporated into the first-order Fermi mechanism, this results in a sharp cutoff in the charged particle spectrum and a previously unanticipated high-energy component in the photon spectrum. In the inverse Compton case, LIV causes a reversion to the Thomson regime at high energies. Applying a synchrotron self-Compton model within the first-order Fermi framework reveals a gradual suppression of the charged particle spectrum, accompanied by the emergence of a new high-energy emission region in the photon spectrum, significantly extending beyond standard expectations.

These results fill an important gap in the study of LIV effects in astroparticle physics, enabling the consistent inclusion of both emission and acceleration processes in the analysis of symmetry-breaking parameters. Furthermore, our study considers both photons and charged particles, laying the groundwork for future multi-messenger observational analyses under the framework of LIV.

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